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ON THE NATURE OF IGNEOUS INTRUSIONS.

In an article in the preceding number of this Journal, certain igneous intrusions in the vicinity of the Black Hills of Dakota, termed plutonic plugs, were described, and the similarity pointed out between the domes of sedimentary beds raised above them and the far greater dome from which the Black Hills have been sculptured. Other mountains of the Black Hills type in Wyoming and Colorado were also mentioned. In the present article I wish to direct attention to the fact that the dome-shaped uplifts referred to, form part of a genetically related series of disturbances caused by subterranean intrusions of igneous rock. Various stages in this series are shown by intruded sheets, laccolites plutonic plugs, and great dome-shaped uplifts of which the Black Hills furnish the type.

Intruded sheets.—As is well known, igneous rocks frequently occur in widely spread sheets, included between but litttle disturbed sedimentary strata. Although the enclosing sedimentary layers are frequently without conspicuous signs of having been disturbed, metamorphism of the sedimentary beds resting on the igneous rock at the surface of contact, furnishes proof that the latter was intruded in a molten condition between planes of bedding, after the sedimentary layers were consolidated. An example of an intruded sheet is furnished by the Palisade trap of New Jersey and New York. Including what is reasonably supposed to be a portion of this sheet, but which is separated from the main exposure by a covering of Cretaceous clays, its length measured along the curve formed by its outcrop is 90 miles. A straight line joining the most northern and most southern exposures is 70 miles in length. The sheet varies in thickness from about 300 feet at Jersey City, to at least 850 feet at

the High Torne, in Rockland county, New York.[1] The breadth of the surface now exposed by erosion, is from one to two miles. The central part of the sheet dips westward, in conformity with the enclosing strata, at an average angle of about 15°, but the dip increases toward the northern extension of the sheet, where irregularities occur. As shown by Darton, the dike that supplied the sheet, is exposed at a few localities on the western margin of the part now uncovered. The sheet does not, therefore, extend indefinitely beneath the sedimentary beds to the westward, as was at one time supposed. The Palisade sheet is remarkable for its extent and thickness, but except in these features, does not illustrate the facts to which I wish to direct attention, so well as many smaller examples of the same nature. In other portions of the Newark system, especially in the Connecticut valley, much thinner intrusive sheets occur, and many similar examples in other regions are familiar to most geologists. One of the best illustrations of the manner in which molten rock has been forced in between the strata of horizontally-bedded sedimentary rocks, which I have observed, may be seen in the precipitous walls of the canyon excavated by Purgatory River in Cretaceous terranes, in southeastern Colorado. The beds cut through in forming this canyon, include a sheet of basaltic rock four or five feet thick, which is exposed for three or four miles on each side of the gorge; so perfectly does it conform with the strata above and below, that even a careful observer seeing its outcropping edge for the first time from the bottom of the canyon, would not mistrust its intrusive origin.

In the case of the intrusive sheet exposed in Purgatory canyon, as already stated, the enclosing strata are horizontal. The same is true of similar sheets in many other regions. It is supposed with good reason that the intrusive sheets of the Newark system were forced in before the associated beds were tilted and faulted. The fact that intruded sheets are of frequent occurrence in regions where stratified rocks are yet horizontal is suggestive.

[1] N. H. DARTON, "The relation of the traps of the Newark system in the New Jersey region," U. S. Geological Survey. Bulletin No. 67, p. 44.

During the intrusion of a sheet of molten rock between horizontal strata, it is evident that the beds above the plane of intrusion must be lifted. The force which lifts the superior layers must be the dynamical energy of the intruded molten rock, aided perhaps by the steam generated when the highly heated magma came in contact with water. If intruded sheets were confined to the side of folds or to regions deformed in other ways, it might be suggested that the force which deformed the rocks tended to separate the strata, thus lessening the work that the intruded rock had to perform in order to make room for itself, but as intrusive sheets seem to be most common if not confined to regions where the receiving terrace is horizontal or was yet undisturbed at the time the intrusion took place, no such assistance can be claimed. That the receiving terrane should be practically horizontal at the time extensive intrusive sheets are formed, seems an essential condition, since folded and tilted strata are apt to be broken and faulted, and would thus furnish passages for the escape of the molten rock forced in among them under great pressure, and dikes and not sheets would result. Also, horizontally stratified beds would offer less resistance to the advance of an intruded sheet among them, than similar beds when folded, since the force necessary to split open the even grain of the horizontal beds, would be less than the force required to separate the contorted grain of folded beds.

Another significant fact, as shown by observation, is that intruded sheets of wide extent at least, are composed of basaltic rocks, that is of the most easily fusible of igneous rocks. Rocks of which basalt may be taken as the type form highly fluid magmas when heated to 2000° or 2500° F., a temperature at which more siliceous rocks like rhyolite, are still solid or at most only viscous. Intruded sheets, therefore, seem to have been formed by the injection of highly fluid magmas under great pressure. Just as easily fusible basaltic lavas, when ejected from volcanoes, tend to spread widely over the surface, so highly fluid magmas, when forced between stratified beds, spread out in thin intruded sheets. As highly viscous magmas, when extruded at

the surface, flow sluggishly and frequently come to rest in thick masses even on steep slopes, it is to be inferred that if such magmas were intruded in a manner similar to that by which sheets of basalt are spread between sedimentary strata, they would expand much less widely. This difference in freedom of flow between magmas that are easily fusible and those that are refractory, appears to be one of the conditions which determines whether a body of highly heated rock intruded among horizontally stratified beds, shall spread widely and form a sheet, or be restricted in its lateral expansion and cause a more local uplift of the strata above it.

Another condition which would influence the behavior of an intruded magma, is the depth in the earth's crust at which the intrusion occurs. Since the rocks above the intruded magma have to be lifted, the higher in the series the intrusion occurs, the less the weight of the rocks above, and the greater the amount of energy available for lateral expansion. If variations in the specific gravity of strata are not considered, the conditions favoring the formation of intruded sheets, increase as the magma approaches the surface, until the tendency of the lifted strata to fracture determines a limit. We should expect, therefore, that intruded sheets would be most numerous in the upper portion of the earth's crust. The correctness of this inference can be tested to some extent by observation. The date at which many intrusive sheets were formed, however, and the amount of subsequent erosion that has taken place, are frequently difficult to determine and space will not permit of the introduction of evidence in this connection. The fact that the edges of intruded sheets are frequently exposed in canyon walls in regions of topographic youth, certainly favors the conclusion that widely extended intrusive sheets are comparatively superficial phenomena.

In order to bring the ideas which I wish to present to a focus, let us consider other phases of igneous intrusion.

Laccolites.—The difference between a widely extended intrusive sheet and a local cistern-like injection of molten rock, or a laccolite, so far as the shape of the intruded mass is concerned,

is mainly in the degree of lateral expansion. In what may be termed their genetic features, these two classes of intrusions are essentially similar. In each case molten rock rises from below into stratified beds, probably through fractures, and on reaching the upper limit of the fractures lateral expansion takes place and the strata above are lifted. The main conditions, as we have seen, which control the extent of the lateral expansion, besides the propelling force and the occurrence of fractures or other openings through which the molten rocks rise, are the fluidity of the magmas, and the depth in the earth's crust at which they reach the upper limit of the passage-way through which they came, and tend to spread horizontally. Under the same conditions respecting temperature and pressure, we should expect refractory magmas to form laccolites, while more easily fusible rock would be more apt to spread out in sheets.[1] We should expect laccolite, therefore, to be composed of less easily fusible rocks than are found in widely extended sheets. Again we may test inference by observation. It is usually conceded that the amount of silica in a rock determines its degree of fusibility. Acid rocks, as a rule, are more refractory than basic rocks. Dana has qualified this conclusion, however, by showing that it is the fusibility of the chief constituent minerals in a lava which determines its mobility. He says: "Trachyte and rhyolite are the least fusible of igneous rocks, because the constituent feldspar, orthoclase, is the least fusible of the feldspars; and basalt or dolerite is one of the most fusible, because the feldspar present, labradorite, is of easy fusibility, and it is combined in the rock with still more fusible augite and pyroxene."

In a recently published report on the laccolitic mountains of

[1] Intruded sheets do occur in connection with the laccolites, and are composed of off-shoots of the same material. Sometimes these sheets, as stated by Cross, extend four or five miles from the main intrusion. As shown in sections of Henry Mountains, given by Gilbert, the associated dikes and sheets are in the disturbed strata above and immediately about the main body of the laccolites. The opening of the deformed strata by the disturbance caused by the principal intrusion appears to have had much to do with the origin of the secondary phenomena. It does not seem to me that the comparatively small sheets originating in this manner furnish an exception to the generalization suggested above.

Utah, Colorado and Arizona, Cross[1] states that the rocks composing these intrusive bodies all belong to a well marked structural type and present but slight variations in mineralogical composition. Plagioclase is the predominant mineral of all the rocks—excepting the quartz-porphyry—and the uniform appearance of its stout white crystals gives character to the whole series. Which of the feldspars composing the group known as *plagioclase*, are most common in these rocks is not clearly stated, but in a table of nineteen analyses, the percentage of silica ranges from 56.62 to 73.50, and of alumina 14.87 to 18.00. The rocks are therefore highly siliceous, and, I think I am justified in concluding, highly refractory, in comparison with the basaltic rocks of which widely extended intrusive sheets are composed.

It appears, therefore, that the nature of an intruded magma, whether highly fluid or viscous, has much to do with the form in which it solidifies. The degree of fusion depends, of course, on the amount of heat. Even the most refractory rocks, when sufficiently heated, will become highly fluid, under normal surface pressure. Since the interior heat of the earth increases with depth, refractory rocks would remain unmelted, or perhaps be partially fused and viscous, at a depth where the most easily fused igneous rocks would be highly fluid. This would lead us to expect also that laccolites would be formed deep in the earth's crust. This inference can be checked by observation. Evidently, if laccolites are now exposed at the earth's surface, the amount of erosion that has taken place in the disturbed beds above them will show how deeply they were originally buried. In the case of the Henry Mountains, Gilbert shows that the domes of stratified beds removed were possibly 7700 feet thick.

The relative specific gravity of intruded magmas may also be expected to influence their behavior, and especially the height to which they would rise under a given pressure, but this seems to be a minor feature of the problem. The force with which magmas are injected is, of course, the main cause which deter-

[1] U. S. Geological Survey. Fourteenth Annual Report, pp. 224, 228.

mines this behavior, but the principle which interests us most at present, is that different magmas under the operation of similar pressure tending to intrude them, would behave differently. The conditions that modify and limit the formation of laccolites have been fully discussed by Gilbert,[1] and need not be reviewed at this time.

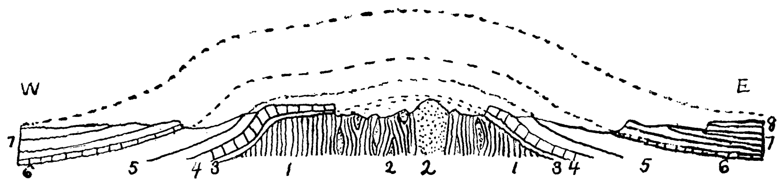
Plutonic plugs.—In a previous article in this JOURNAL, already referred to, I have directed attention to the plug-like intrusions that occur in the Black Hills region. These intruded masses have been classed as laccolites by Crosby, and possibly the variation they present from that type is not sufficient to necessitate a separate consideration. They occur in a region where the stratified rock into which they were forced are essentially horizontal, and where dikes and other evidences of fracture are absent, and where deep erosion has occurred. They are formed of refractory acid rock. The principal mineral constituent, according to Casswell, is always sanadine.

The Black Hills of Dakota.—As pointed out in the essay referred to above, and as previously stated by Newton in his report on the Black Hills, the domes of sedimentary strata upheaved by the intrusion of plugs of igneous rock in the case of the Sun Dance hills, Inyan Kara, etc., are structurally identical with the vast Black Hills dome. In each case previously horizontal strata were raised by a force acting from below vertically upward, so as to form a dome from the summit of which the layers dip away in all directions. The dome known as Little Sun Dance hill is unbroken by fractures and the summit of the plug of igneous rock inferred to exist beneath it, is not exposed. The absence of dikes in connection with the associated uplifts indicates that they, also, were not fractured as they rose, so as to allow the fluid rock beneath to escape. The absence of dikes indicates that the intrusion of the plugs took place at great depths, and that the upraised strata were under heavy pressure. The strata, after being upraised, were certainly of greater superficial extent than previously, when horizontal, and a stretching

[1] Report on the geology of the Henry Mountains.

and thinning of the beds over the summit of the dome is to be inferred, but thus far has not been observed.

The Little Sun Dance dome is about a mile in diameter. The Inyan Kara dome measures about two miles in diameter. The similar dome from which Warren Peak has been sculptured, was two or three by eight miles in diameter. The Black Hills dome, as shown by Newton and Gilbert, is less regular in ground



IDEAL CROSS-SECTION OF THE BLACK HILLS.

Vertical scale 5–6 times horizontal. Dotted lines indicate portion of uplift removed by erosion.

1. Archæan slates and schists.
2. Granite.
3. Potsdam unconformably on 1 and 2.
4. Carboniferous.
5. Red beds.
6. Jura.
7. Cretaceous.
8. White River Tertiary unconformably on 7.

plan than those just mentioned, and measures 70 by 160 miles in diameter.

The plugs of igneous rock which lead to the elevation of the Inyan Kara and several associated domes, have been exposed by erosion, and rise boldly in the center of the encircling rings formed by the truncation of the domes that formerly arched over and concealed them. In the center of the concentric outcrops of stratified rocks forming the outskirts of the Black Hills, there is a mass of schists into which a core of granitic rock has been intruded. The succession of stratified rocks forming the dome, and their relation to the schists and granites within, is shown in the following section copied from Newton and Gilbert. It is to be remembered that any cross section through the Black Hills uplift would show the same structure, although the details would be varied.

The schists shown in the central part of the section, belong to the series of stratified rock resting on them, so far as the origin

and general structure of the uplift are concerned, and shared in the disturbance that elevated them. Whether the core of intruded granite answers to the plutonic plugs forming the cores of the smaller domes or has itself been elevated by an intrusion of molten rocks beneath, will be considered in advance.

Under this view of the origin of the Black Hills dome, the supposed intrusion of molten rock took place deep below the surface, and on account of the vast weight to be lifted, and probably also by reason of its viscosity, did not expand into a broad sheet, but as in the case of true laccolites, and plutonic plugs, produced a local elevation. The deeper the horizon at which the intruded rock expanded, the broader would be the dome formed above it. The outline of the dome raised on the surface would depend on the form of the cistern of molten rock beneath, and perhaps on the dip of stratified beds before the intrusion occurred. If the subterranean cistern was supplied through an extended fissure, an elongated dome or a ridge-like elevation at the surface would result. The domes produced by the injection of plutonic plugs, as already stated, are nearly circular, but the major axis of the Black Hills dome is double the length of the minor axis. The form that the elongated Black Hills dome would present, had there been no erosion, is shown on a contour map by Newton and Gilbert.[1]

The influence of dip on the form of an uplift produced in the manner above considered, is probably not important, as it is doubtful if such deformation occurs in rocks that are not essentially horizontal.

Mountains of the same type as the Black Hills but in which the difference between the horizontal axes is greater, occur in the same general region.

The mountains of Wyoming and Colorado.—The Big Horn Mountains, Wyoming, are of the same type as the Black Hills uplift, but the dome from which they were sculptured was more elongated than is the case of the Black Hills dome. The trend of the range is approximately northwest and southeast, but is

[1] Report on the Geology of the Black Hills, plate opposite page 208.

concave on the west, the longer diameter of the now truncated dome is 160 miles and its shorter diameter about 50 miles. At the south this uplift merges with another of similar character which trends more nearly east and west and has been deeply eroded. Its central mass of weathered granite forms the Wind River Mountains. Mountains having the same structure, extend southward into Colorado, and form several ranges designated by Powell as the Park Mountains. Each of these dome-like uplifts of Wyoming and Colorado has been deeply eroded, and broad central cores of granite exposed and sculptured into bold topographic forms. Sections through the mountains of Colorado from east to west, published in the "Atlas of Colorado," by Hayden, and the atlas accompanying the reports of the Fortieth Parallel Survey, show great central masses of what is termed metamorphic granite. On the flanks of these central masses the sedimentary strata underlying the adjacent plains, are sharply upturned. In many instances the central granitic cores are from 20 to 30 and even 50 to 60 or more miles across.

These dome-like arches are clearly not anticlinical folds; although, that such was their origin has frequently been stated. Nothing in the Appalachian or other similar ranges, formed by the crumpling of stratified beds by lateral compression, corresponds with them. Experiments with plastic material in illustration of the formation of anticlines and synclines, do not suggest that such broad, simple arches surrounded by horizontal strata can be produced in the same manner. These great upward bulges are similar to the Black Hills dome, the only conspicuous difference being that they are much elongated. If we arrange in a series, cross sections of the Black Hills, Big Horn, and Wind River Mountains and of several of the ranges included in the Park Mountains, it will be seen that a single type of uplift is shown in all cases. The same fact will appear also if restorations of the various domes as they would appear had there been no erosion, are placed side by side. That several of the more prominent ranges of Wyoming and eastern Colorado are of one type, was recognized by Hayden, who considers them, however,

as have others, of the nature of anticlinals produced by lateral compression. He says: [1]

> In general terms, while the details are extremely complicated, we may express the structure of a belt of country known as the Sawatch range (in east-central Colorado), eighty miles in length from north to south, and at least forty from east to west as a single wedge of granite, thrust upward, and the sedimentary rocks inclined from either side. The illustration of which the Sawatch range is the central mass is probably on a grander scale than any other in the West, but there are abundant examples of smaller size. The Black Hills of Dakota, the Laramie range, Big Horn, Wind River and many others are of the same type.

The cores exposed in the Black Hills, Big Horn and other mountains referred to above, are of granite. Whether these granitic centers answer to the plutonic plugs in the smaller domes to the northward of the Black Hills, or belong structurally to the sedimentary beds upturned on their flanks, and have themselves been elevated by intrusions beneath, is not clear. I am inclined to the hypothesis, however, that the granite was the floor on which the sedimentary beds were deposited and that it has itself been elevated with them.

The magnitude of the elongated domes from which the present mountains of Colorado and Wyoming have been sculptured, might perhaps be urged as an objection to the view of their origin here expressed. As it will tend to make us more cautious if the size of the problem we have attacked is fully realized, let us endeavor to form a mental conception of the region referred to as it would appear under this hypothesis, if unaffected by erosion.

On the summit of Mt. Lincoln, Colorado, 14,297 feet above the sea, there are, according to Hayden, clastic beds belonging to the same series as the strata upturned on the flanks of the mountains of which Mt. Lincoln is one of the dominant peaks. No one who is familiar with the geology of Colorado will dispute, I fancy, that this and other similar evidence, may be taken as proof that the granite now forming the central

[1] U. S. Geological and Geographical Survey of the Territories, annual report for the year 1873, p. 49.

peaks of the several ranges termed the Park Mountains, was once covered by an extension of the formations now found beneath the intervening valley, and upturned on the flanks of the uplifts.

As the central cores of granite now rise between seven and eight thousand feet above the adjacent border of the Great Plains, the refilling of the gorges and valleys excavated in their sides, so as to restore what would have been the surface contour of the granite had there been no erosion, would produce an elongated dome rising at least seven or eight thousand feet above the adjacent plain on the east. If we add to the surface of this dome the thickness of sedimentary beds now upturned in its eroded flanks, its height will be increased by seven or eight thousand feet; this being the approximate average thickness of the upturned border of the strata that extend horizontally beneath the Great Plains.

The most severe test of the hypothesis before us, in respect to the magnitude of the results reached, is furnished by what is known as the Front Range of the Rockies in Colorado and Wyoming. This range is probably not the result of the wearing away of a single dome, but as the central granite core now exposed is continuous from Central Wyoming to southeastern Colorado, a distance measured along the curve of the outcrop, of about 400 miles, we will consider it for the present, as an individual uplift. The average breadth of the granite is between twenty and twenty-five miles. The great elongated dome from which the Front Range of the Rockies has been sculptured, would therefore if uneroded, have a length in excess of 400 miles, a breadth of probably 40 or 50 miles and a height above the level of Denver of 15,000 to 16,000 feet.

This result reached by pressing our hypothesis to its logical conclusion—and assuming in order to make the test as severe as possible, that the Front Range is a single uplift—is startling, it is true, but no more so than the measures of the amount of erosion that have been obtained in an adjacent region. In the Uinta Mountains, Powell finds that the mean thickness of rock

which has been eroded away from a large area, is 18,500 feet, and in the axial region of the mountains, is 25,000 feet.

From the broad oval summit of the great dome we have restored in fancy by prolonging the remnants of the base of the arch over the central granitic peaks, we can see lesser domes which form a series and lead step by step down to the Little Sun Dance dome, a mile in diameter, the inner layers of which remain to this day unbroken.

As the type of mountain briefly described above is distinct from other types usually recognized, it will be convenient to designate it by an appropriate name. To meet this want, I venture to suggest that uplifts which owe their origin to the intrusion of a molten magma into the rocks beneath them, be termed *subtuberant mountains*. They may be fancied to originate from the growth of a tuber within the earth's crust.

General conclusions.—From the facts to which attention has been directed, it seems to me that a sequence is traceable between: (1) Intruded sheets of the Palisade type, formed by highly fluid magmas spreading widely between horizontally stratified beds, and lifting a broad cover without producing conspicuous topographic changes or marked disturbances in the upraised beds. (2) More local intrusions of less fluid magmas forced into horizontally stratified beds, which raised the strata above into domes, as is the case of the Henry Mountains, the Sun Dance hills, etc., and (3) deeply seated intrusions probably of highly viscous magmas, which raised vast domes of sedimentary rock and the floor of metamorphic rock on which they repose, as in the case of the Black Hills, Big Horn, and Park Mountains.

To the question, whence came the force that was enabled to intrude sheets of molten material scores and even hundreds of square miles in area, between sedimentary layers, and lift beds of rock of the same extent and, in at least some instances, many hundreds of feet thick; or elevate domes from 50 to 200 miles or more in diameter, to a height of several thousand feet, only general answers can be given.

On the theory that the interior of the earth is in a highly

heated and plastic condition and enclosed in a more rigid shell which contracts as it cools, a force is brought to bear on the plastic interior which tends to squeeze it out whenever an opportunity is afforded. The idea is not that the crust of the earth is a cold and solid shell enclosing a molten interior, the surface of contact between the two being sharply defined; but rather that the highly heated and plastic interior passes by insensible gradations into a cooler and more solid exterior, the outer surface of which is cold and rigid. The crust is still losing heat and consequently contracting and thus brings a pressure to bear not only on the interior mass but on the material forming the crust itself. On account of irregularities and unequal cooling, regions well within what may be termed the crust, may still be in a molten condition. Such bodies of plastic material may differ from the rocks enclosing them, as well as vary in composition among themselves, by reason of having reached different stages in the process of change from a molten to a solid condition. Here again we are departing from observed conditions, and have only the imagination to guide us, as there are no tests available by which the truth of our conceptions can be verified.

Under the conditions assumed, when a fissure is formed in the earth's crust, the deeply seated fluid or plastic material within, is forced out and becomes more and more fluid as it rises and pressure is relieved, unless this tendency is more than counteracted by the decrease of fluidity due to loss of heat. When such fissures open a way to the surface volcanic phenomena ensue. If the fissures do not reach the surface but terminate in horizontally stratified rocks, the molten material which rises in them may spread more or less horizontally between the strata and form sheets, or exert its force locally and cause a dome to rise, according to its viscosity, the depth below the surface, etc.

Nothing less than the force produced by the contraction of a cooling globe seems adequate to account for the results to which attention has been directed. The slowness with which the earth has lost heat and the consequent slowness with which contraction has acted on the still plastic interior or still plastic reservoirs

in the crust itself, is in harmony with the gradual bending of strata thousands of feet in thickness, as seen in the Black Hills, Big Horn Mountains, etc., without producing fractures through which the igneous material could escape.

Certain broad physical features of the earth seem in harmony, also, with the views here advanced. It has long been recognized that volcanoes are arranged about the borders of continents, and on the ocean's floor. So far as the association of oceanic waters is concerned with the origin of volcanoes, this arrangement is now considered accidental. But as shown by Dana, volcanoes mark lines of weakness in the earth's crust. These lines of weakness may reasonably be supposed to be the direction taken by the fractures during an early stage in the cooling of the globe and to have continued to be the lines of weakness along which movements have taken place from time to time, down to our own day. In the central portions of continental areas, active and recently extinct volcanoes are much less numerous than near continental margins. In the case of those that do occur far inland, as in the Great Basin region, there is plain evidence that the rocks of the earth's crust have been broken, and the region is as much a line of weakness as if it chanced to be adjacent to the sea.

While active and recently extinct volcanoes are notably absent from the central portions of continental areas, it is equally true so far as can be judged from available data, that subtuberant mountains are confined to such central regions. This follows also from the conclusions that broad areas of horizontal and unbroken stratified rocks are favorable for the formation of extensive intrusions.

The central portions of continental areas although not lines of weakness in the sense used by Dana, are regions of denudation and, as has been recognized by several American geologists, may be considered as relatively light areas, in comparison with continental borders, where maximum sedimentation takes place. It is in regions where the earth's crust is relatively light, when fractures are absent, and where the strata are essentially horizon-

tal, that pressure brought to bear on the plastic interior—either by reason of the cooling and contraction of the earth's crust, or by the shifting of material on the surface, in the constantly active processes of denudation, transportation and sedimentation—would most reasonably be expected to cause the rocks to bulge upward into domes.

If the above considerations are well founded we should expect to find subtuberant uplifts in the central portions of continental areas, but not about their borders. Here, again, it would be well to check inference by observation, but so far as I am aware, mountains of the type referred to, have not been recognized outside of the United States. Although unable to verify our conclusion, at present, we can leave it as a prediction, the truth or fallacy of which will appear as exploration is continued.

Analogies between subterranean and surface igneous phenomena.—Certain analogies between the phenomena associated with subterranean intrusions and with surface extrusions or volcanoes, are of interest.

Quiet eruptions of highly liquid basaltic lava, like those characteristic of the Hawaiian volcanoes, are represented below the surface by widely extended intrusive sheets of similar material. The thick and sluggish volcanic flows of rhyolite of the character to be seen on the side of the Mono craters, California, are suggested by the cistern-like intrusions of refractory porphyrite, forming laccolites, and still more strongly by plutonic plugs in which no lateral expansion has been recognized. Fissure eruptions, like those that furnished the Columbia lava of Idaho, Washington and Oregon, or the Deccan traps of India, so far as the energy manifest, and the extent of topographic changes produced, are concerned, find more than a counterpart in subtuberant mountains.

Extremely violent volcanic explosions occur when large bodies of water come in contact with molten lava. A molten magma rising from a deeply seated source in the earth's crust, as a rule, invades strata that are more and more highly water-charged, the nearer it approaches the surface. A secondary

result of such an intrusion is the generation of steam. In the case of the intrusion of a plutonic plug for example, steam may be generated and assist in raising the dome that is formed in the stratified beds above. When a plutonic plug on approaching the surface comes in contact with subterranean water, sufficient steam may be generated to blow away the dome above. Surface explosions sometimes remove large portions of volcanic mountains, as in the case of Krakatoa, Somma, Santorin, Barren Island, Coseguina, Crater Lake, etc.; plutonic explosions may reasonably be supposed to remove domes of stratified rock (consisting either wholly of sedimentary beds, or made up in part of lava sheets), and form crater-like depressions termed crater-rings, calderas, etc., as in the case of Coon Butte, Arizona; Lonas Lake, India; and still greater cavities, like those occupied by Lakes Bolsena and Bracciano, Italy, the former of which is circular and six and one-half miles in diameter, and the latter less regular, with a north and south diameter of ten and one-quarter miles, and a breadth of nine miles.

The breaking of the steam bubbles that rise through the boiling lava in the crater of Vesuvius cause the summit of the mountain to tremble with miniature earthquake shocks. When the throat of the volcano becomes clogged, steam generated within breaks through the obstruction or rends the mountain with such violence that the region for miles around is severely shaken. Subterranean intrusions of molten rock on coming in contact with water, may reasonably be supposed to cause similar steam explosions of which the only surface manifestations would be earthquake shocks.

Since my essay on the plutonic plugs of the Black Hills region was published, my attention has been directed to the fact that the rocks, of which some of the plugs are composed, have been recently studied in the light of more modern petrographical methods than were employed by Caswell. L. V. Pirsson, states, in the Am. Jour. Sci., Vol. XLVII., 1894, pp. 341–346, that the rock forming the cores of Mato Teepee and the Little

Missouri Buttes, is phonolite, instead of sanadine-trachyte, the conspicuous feldspar being "soda-orthoclase or anorthoclase." A chemical analysis of the rock gave SiO_2 61.08, and Al_2O_3 18.71. "A vertical dike about fifty feet wide, cutting through the schist and Palæozoic series in the mountains south of Deadwood," observed by C. E. Beecher, is also mentioned.

Observations by W. M. Dawson, W. H. Weed and L. V. Pirsson, seem to show that domes with cores of plutonic rock and surrounded by horizontally stratified beds, similar to the domes with plutonic plugs in the neighborhood of the Black Hills, form the Sweet Grass Hills and Zogo Peak, Montana.[1]

Errata.—The titles of Figs. A and B, Plate II., Vol. IV. of this JOURNAL, should be transposed. The title for Fig. A should read, "Little Missouri Buttes from the East."

ISRAEL C. RUSSELL.

[1] "Report upon Country in the Vicinity of Bow and Belly Rivers, Northwest Territory, in Geol. and Nat. Hist. Sur. and Mus. of Canada, Report of Progress, 1882–3–4, c. pp. 16, 45.

W. H. WEED and L. V. PIRSSON, "On the Igneous Rocks of the Sweet Grass Hills, Montana," in Am. Jour. Sci., Vol. L., 1895, pp. 309–313.

L. V. PIRSSON, "On Some Phonolitic Rocks from Montana," in Am. Jour. Sci., Vol. L., 1895, pp. 394–399.

W. H. WEED and L. V. PIRSSON, "Igneous Rocks of Zogo Peak, Montana," in Am. Jour. Sci., Vol. L., 1895, pp. 467–479.